

THE LEVER OF RICHES



*Technological Creativity
and Economic Progress*

JOEL MOKYR

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and Economic Progress

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*To the Memory of My Mother
Who did it all by Herself*

Preface

This is a book about technological creativity. Why would an economic historian write such a book? Technology is about how to make things and services that are useful and enjoyable, that is, it is about production. The difference between rich nations and poor nations is not, as Ernest Hemingway said, that the rich have more money than the poor, but that rich nations produce more goods and services. One reason they can do so is because their technology is better; that is, their ability to control and manipulate nature and people for productive ends is superior. If the West is on the whole comfortable, even opulent, compared to the appalling poverty still rampant in most of Asia and Africa, it is in large part thanks to its technology. As one author has put it, we have to “give credit to just those dull, everyday, pragmatic, honest betterments in simple technology . . . that were taking place in Europe . . . doses of which would wash away much of the misery in the world today” (Jones, 1981, p. 69). Western technological superiority has deep historical roots, and can only be understood—if at all—by an analysis that is willing to look back centuries, even millennia. To be sure, technology cannot take all the credit: the development of law, trade, administration, and institutions were all part of the story. Yet, as I shall try to show, technological creativity was at the very base of the rise of the West. It was the lever of its riches.

How does technology change? Like science and art, it changes through human creativity, that rare and mysterious phenomenon in which a human being arrives at an insight or act that has never been accomplished before. Of course, technological creativity is quite different from artistic or scientific creativity. It tends to be more down-to-earth, with such mundane characteristics as dexterity and greed at the center of the act. Yet it does share with the arts and the sciences its occasional dependence on inspiration, luck, serendipity, genius, and the unexplained drive of people to go somewhere where none has gone before. Although some portion of invention comes today from the cold and calculating minds of Research and Development engineers in white labcoats worn over three-piece-suits, much of the technological creativity that made our economic world what it

is came from different sources. I will make an effort to describe and then explain this creativity. However, it is a task that can never be carried out completely. At some level we stand in uncomprehending awe before the miracle of human genius. We can no more "explain" the breakthroughs inside the minds of a Montgolfier or a Westinghouse than we can explain what went on inside the head of Beethoven when he wrote the *Eroica*. Economists and historians alike realize that there is a deep difference between *homo economicus* and *homo creativus*. One makes the most of what nature permits him to have. The other rebels against nature's dictates. Technological creativity, like all creativity, is an act of rebellion. Without it, we would all still live nasty and short lives of toil, drudgery, and discomfort.

It is always a pleasant task to thank the many friends and colleagues who have made this book possible, and are responsible in some way for many of the arguments and opinions expressed in it. As my name appears on the title page and theirs do not, however, I alone shall carry the blame for all errors and misstatements and suffer the wrath of the wronged and misquoted.

The project began many years ago when my former colleague F. Michael Scherer walked into my office at the Northwestern University Economics Department and proposed a "small monograph" on the history of technological progress that, he assured me, would take me at most a few months over the summer to write. I did not buy the Brooklyn Bridge from him that afternoon, but I did make a promise that would result in many long nights in libraries and in front of my wordprocessor. Mike has thus sown the seed for this book, and while it was I who had to carry it to term, he has been supportive and helpful throughout the project. I can only hope that the readers will not hold anything in this book against him.

Intellectually, the inspiration for this book came from a variety of sources, many of which I cannot recall. Teaching economic history for fourteen years means that one inevitably absorbs large amounts of information that cannot possibly be traced to their sources. A number of books, however, stick out as I find myself going back to them again and again for insight, inspiration, and information. They are David Landes' *Unbound Prometheus*, Lynn White's *Medieval Religion and Technology*, Eric Jones's *European Miracle*, Abbott Payson Usher's *History of Mechanical Inventions*, and Donald Cardwell's *Turning Points in Western Technology*.

Of my Northwestern colleagues, I would like to mention those who have not only read the manuscript in its numerous half-baked versions and gave me good advice and encouragement, but also provided the comradeship and emotional support few can do without. They are Louis Cain, Charles Calomiris, Karl de Schweinitz, Jack

Goldstone, David Hull, Jonathan R. T. Hughes, and Sarah Maza. Many of my graduate students, upon whom successive versions of the manuscript were inflicted, made valuable contributions. Among them, I am particularly grateful to Katherine Anderson, Avner Greif, Paul Huck, Lynne Kiesling, John Nye, Gabriel Sensenbrenner, Dan Shiman, Richard Szostak, and Martha Williams. I have come to realize the profound truth in Rabbi Akiva's famous dictum, that he learned much from his teachers, more from his colleagues, and most from his students.

Outside Northwestern, my greatest debt as always is to Cormac Ó Gráda, whose almost legendary patience and wisdom have been an indispensable resource to me for many years now. The manuscript was read by an embarrassingly long list of other friends, who found an equally embarrassing list of errors and omissions, and made many invalid complaints, the most vociferous of which was that I did not write the book they would have if they had written it. This list contains Robert C. Allen, William Baumol, Reuven Brenner, Julia Burns, Paul A. David, Jan De Vries, Stefano Fenoaltea, George Grantham, C. Knick Harley, Dan Headrick, Eric Jones, William McNeill, Donald McCloskey, William N. Parker, Richard Szostak, Andrew Watson, K. D. White, and Bing Wong. A conference of the All University of California group in Economic History in October 1988 discussed an earlier version of this book and provided me with many good ideas, not all of which I could carry out.

My research assistant Erik Zehender loyally assisted me in plundering the shelves of the Northwestern Libraries for three years, as well as provide the Interlibrary Loan office with a medium run increase in the demand for their services. Mrs. Barbara Karni edited the manuscript with her usual thoroughness and competence. Mr. Herbert Addison at Oxford University Press contributed generously from his knowledge of books and publishing to this book in its final stages. The secretaries at the Northwestern department of economics, Mrs. Angie Campbell, Mrs. Ann Roth, and Mrs. Florence Stein, have given me their help and support over many years. A special debt is acknowledged to Mr. Jack Repcheck of Princeton University Press.

My wife Margalit was always at my side when I needed her. My daughters Naama and Betsy were there even at times when I did not.

Evanston, IL
January 1990

J.M.

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PART ONE

ECONOMIC GROWTH
AND
TECHNOLOGICAL
PROGRESS

CHAPTER ONE

Introduction

Past economic growth is crucial to the material aspects of our existence: the best predictor of the living standard that a newborn baby can expect to enjoy is the accident of where he or she is born. There is very little in common between the quality of life that can be expected by an average person born in, say, rural Cameroon or urban Java, and one born in Greenwich, Connecticut or Oslo, Norway. The difference is captured by a somewhat artificial statistic concocted by economists known as national income or gross national product per capita. The current level of this magnitude is determined by its past. In economics, history is destiny.

To say, then, that a country is rich is to say that it experienced economic growth in the past. While this statement describes everything, it explains nothing. The causes of economic growth—why some societies grew rich and others did not—have been pondered by economists, sociologists, historians, and philosophers for centuries. This book is another attempt to struggle with this issue of issues. It focuses on what I believe to have been one key ingredient of economic growth: technological creativity. The book puts forth an argument about the causes of economic progress, about rising living standards, about improving nutrition, clothing, housing, and health, and about reducing toil, drudgery, famine, and disease. Technological progress has been one of the most potent forces in history in that it has provided society with what economists call a “free lunch,” that is, an increase in output that is not commensurate with the increase in effort and cost necessary to bring it about.

This view of technological change is inconsistent with one of the most pervasive half-truths that economists teach their students, the hackneyed aphorism that there is no such thing as a free lunch. It is the purpose of this book to highlight the greatest counterexample to this statement.¹ Economic history is full of examples of free lunches,

1. For a similar statement, rare among economists, see Kamien and Schwartz (1982, p. 216). Kamien and Schwartz, too, regard technological change as a “trick” that makes it possible to avoid making a choice when faced with Samuelson’s famous query “which

as well as (more frequently) very cheap lunches. At the same time, there are endless instances of very expensive meals that ended up inedible and in some cases lethal. To phrase it differently, technological change is primarily the study of what economists call outward shifts of the production possibility frontier, that is, increases in the productive potential of the economy. Through most of history, however, societies have not been *on* the frontier, where they fully exploited their resources, but at a point inside it, where waste and inefficiency meant that living standards were lower than they would have been if the resources available had been deployed efficiently. War, discrimination, unemployment, superstition, barriers to trade and economic freedom, resource mismanagement, and many other instances of human inefficiency meant that only a fraction of the resource potential available was utilized to produce goods that conveyed economic utility. By reducing waste, economies could increase their living standards without increasing the amounts of labor and other resources needed. Although such an increase might well be regarded as some kind of free lunch, it is not the kind I shall be concerned with. Instead, I shall focus on shifts *of* the production frontier itself, that is, increases in the productive potential of the economy, as they are most frequently identified with economic growth.

Not all economic growth is necessarily related to technology. Roughly speaking, economic growth can occur as the result of four distinct processes:

1. Investment (increases in the capital stock). The productivity of labor, and with it the average standard of living, depends on the quantities and qualities of the equipment and tools an average worker has at his or her disposal (known among economists as the capital-labor ratio). When capital accumulates at a rate faster than the growth of the labor force, so that each worker has increasingly more capital to work with, economic growth will take place; that is, output per capita will increase. We can call this kind of phenomenon *Solovian growth*, in honor of Robert Solow, who laid the foundation of the modern theory of economic growth. At first glance, this type of growth involves no free lunch. Investment is made possible by saving; to save by definition is to refrain from consumption in the present in order to consume more in the future. Thus, all future benefits are paid for by a willingness to abstain in the present, which is in itself undesirable and thus costly.

one," and have "both." Their analysis is cast largely in terms of a modern market in which research and development is carried out in a systematic way. McCloskey (1981, p. 117) points out that the Industrial Revolution must be "a bitter disappointment to the scientists of scarcity" and refers to the no-free-lunch dogma as "a mildly comical jargon."

2. Commercial expansion. It is the standard fare of intermediate courses in microeconomics to illustrate that an increase in the exchange of goods, services, labor, or capital can be beneficial to all partners involved. Abstracting from the cost of transacting, the creation of commerce and voluntary exchange between two previously disjoint units—be they individuals, villages, regions, countries, or continents—leads to increases in income for both partners. These gains are known as the gains from trade and represent a good example of a free lunch. Trade, as Adam Smith pointed out in 1776, leads to a growth in the *Wealth of Nations*. Smith's mechanism of growth was based on the idea that a finer division of labor leads to productivity growth through specialization and the adaptation of skills to tasks. Economic growth caused by an increase in trade may be termed *Smithian growth* (following Parker, 1984).² Trade is created by a decline in transactions costs (that is, the costs involved in bartering or buying and selling goods and services on the market), or the improved assignment and enforcement of property rights. It is, however, not the kind of free lunch I shall be much concerned with in this book.

3. Scale or size effects. It is sometimes maintained that population growth itself can lead to per capita income growth (e.g., Simon, 1977; Boserup, 1981). Clearly, if the division of labor increases prosperity, then for very small populations growth in numbers alone would make specialization possible and lead to gains in output. Moreover, at least up to some point there are fixed costs and indivisibilities, such as roads, schools, property-rights enforcement agencies, and so on, that can be deployed effectively only for relatively large populations (North, 1981). When an increase in the scale of the economy by itself leads to growth in the economy's per capita productive potential through the mere multiplication of numbers, it will appear to individuals as a free lunch. A continuous growth in population, however, will increase the pressure of population on other resources that do not grow (such as land and other natural resources) or grow more slowly, and the economy will move from a regime of increasing to a regime of diminishing returns. When this crowding effect begins to be felt, further population growth will lead to intensification of production, which causes average income to decline. It is still possible for other factors to offset diminishing returns, so that population

2. The term is slightly misleading because Adam Smith emphasized the gains from trade that derived from the division of labor, specialization, and the resulting productivity gains. The standard gains from trade model, developed by David Ricardo, is based on comparative advantage and does not depend on the Smithian notions of specialization. Adam Smith emphasized demand as the limit to specialization, while Ricardo's model holds independent of the size of the market.

growth could be *accompanied* by economic growth. But it would be incorrect to infer in such a case that population growth *causes* economic growth.

4. Increases in the stock of human knowledge, which includes technological progress proper, as well as changes in institutions. Again following Parker, I shall refer to this type of process as *Schumpeterian growth*, in honor of Joseph A. Schumpeter, whom we will encounter repeatedly later in this book. Parker (1984, p. 191) defined Schumpeterian growth as "capitalist expansion deriving from continuous, though fluctuating, technological change and innovation, financed by the extension of credit." This book is indeed about little else but technological change and innovation. By technological progress I mean any change in the application of information to the production process in such a way as to increase efficiency, resulting either in the production of a given output with fewer resources (i.e., lower costs), or the production of better or new products. Unlike Parker, however, I believe we should not confine the idea of Schumpeterian growth to capitalist expansion financed by credit alone. Technological progress predated capitalism and credit by many centuries, and may well outlive capitalism by at least as long.

The choice of the words "application of information" is deliberate: much growth, as we shall see, is derived from the deployment of previously available information rather than the generation of altogether new knowledge (Rosenberg, 1982, p. 143). When all is said and done, from the point of view of economic growth it does not really matter whether income grows because of the application of *entirely new* information to production even if a proper definition of what "new" exactly means here could be agreed upon, or the diffusion of *existing* information to new users.

The historical record of technological change is uneven and spasmodic. Some brief spans in the history of a particular nation—such as Britain between 1760 and 1800 or the United States after 1945—are enormously rich in technological change. These peaks are often followed by periods during which technological progress peters out. Why does that happen? Although economists, sociologists, and historians have written extensively about this question, they have found its explanation elusive. One economic historian (Thomson, 1984, p. 243) has quipped that "technical change is like God. It is much discussed, worshipped by some, rejected by others, but little understood." There are good reasons for this lack of understanding. The diversity of technological history is such that almost any point can be contradicted with a counterexample. Picking up empirical regularities in this massive amount of qualitative and often uncertain and incomplete information is hazardous. Yet without it the painstaking

work of technological historians seems pointless, and the role of technology in the history of our economies will remain incomprehensible.

When the resource basis of an economy expands, it can do one of two things: it can enjoy higher living standards, or it can, in H. G. Wells's famous phrase, "spend the gifts of nature on the mere insensate multiplication of common life." In recent history, economic growth has occurred *despite* population growth. Before that, as Malthus and the classical political economists never tired of pointing out, the growth of population relentlessly devoured the fruits of productivity growth, and living standards, as far as we can measure them, changed little in the very long run. It might, therefore, make sense, for some purposes, to define growth as an increase in total income rather than income per capita. This is the approach taken by Jones (1988).

The literature produced by modern economists on technological change is vast.³ All work on economic growth recognizes the existence of a "residual," a part of economic growth that cannot be explained by more capital or more labor, and that thus must to some extent be regarded as a free lunch. Technological change seems a natural candidate to explain this residual and has sometimes been equated with it forthwith. This literature has not, however, been very successful in explaining why some societies are technologically more creative than others. It is rarely informed by economic history, confining itself mostly to the post-1945 period. It is also rarely informed by technological history. When a historian of technology, such as Abbott P. Usher, is cited, it is more for his interesting but speculative application of Gestalt psychology to invention than for his enormous knowledge of how machines actually evolved over time (see, for instance, Thirtle and Ruttan, 1987, pp. 2–5). Economists typically approach the explanation of technological change by considering the relationship between demand and supply variables, research and development, and productivity growth. In so doing, they implicitly treat technology as an input—albeit one with peculiar features—that is produced and sold in the market for research and development. Such a market analysis may or may not be a useful description of the post-1945 period (Jewkes, Sawers, and Stillerman, 1969; Langrish et al., 1972). It is clear, however, that for an explanation of the diffusion of wind power in medieval Europe, the adoption of iron casting in China during the Han dynasty, or the adoption of intensive husbandry in seventeenth-century Britain, such a framework is wholly inappropriate. Technological change throughout most of history can

3. For recent surveys, see Thirtle and Ruttan (1987); Baldwin and Scott (1987); Coombs et al. (1987); Wyatt (1986).

hardly be regarded as the consequence of an orderly process of research and development. It possessed few elements of planning and precise cost-benefit calculation. How, then, to explain it?

Once the economist ventures outside the safe realm of traditional microeconomics and agrees to consider extraeconomic factors, he or she often discovers that events are hopelessly overdetermined, that is, there are many plausible explanations for every phenomenon. Theories of technological change based on geographic, political, religious, military, and scientific factors are typically easy to concoct and hard to reject. Many explanations make sense. But are they likely to be correct? Posing the question in this way may not be very useful; it might be better to ask whether such explanations are persuasive. Can we amass enough evidence to show that a particular theory is supported by facts and not just logic? In what follows, I shall try to pursue such a methodology.

By focusing on Schumpeterian growth I am not downgrading other forms of economic growth. Technological change unaccompanied by other forms of growth is rare. The four forms of growth reinforce each other in many complex ways. For example, a widely held view of technological change maintains that much technological change is embodied in new capital goods, so that in the absence of capital accumulation, technological change would be slow. To the extent that this view is correct, Solovian growth and Schumpeterian growth go hand in hand. Schumpeterian growth can also lead to Smithian growth, as it did, for example, when technical advances in shipping led to increased gains from trade by lowering transportation costs. To keep matters relatively simple, I shall focus here on technological change proper, dealing with other forms of economic growth only insofar as they touch upon technological change directly.

The study of technological change inevitably must move between the aggregate and the individual levels of analysis. Economic growth itself is by definition an aggregate process, the processes of invention and adoption usually being carried out by small units (individuals or enterprises). The economic historian is therefore directed to the macrofoundations of technological creativity, that is to say, what kind of social environment makes individuals innovative, what kind of stimuli, incentives, and institutions create an economy that encourages technological creativity? Technological creativity is analyzed largely as a social, rather than an individual, phenomenon. In other words, the question I am interested in here is not why some individuals are more creative than others, but why were and are there societies that have more creative individuals in them than others? It is that question that lies at the foundation of the issue of issues, why

does economic growth (at least of the Schumpeterian type) occur in some societies and not in others.

It may turn out, as Heertje (1983, p. 46) has put it, that technological change cannot be explained. By that he means, I think, that standard economic theory which deals, after all, with rational choices subject to known constraints, faces a dilemma in dealing with technological creativity. Technological change involves an attack by an individual on a constraint that everyone else takes as given. The methodology of economics is largely based on the idea that economic agents try to do as well as they can given their constraints, but by definition can do nothing to change these constraints themselves. Therefore, much of the research in the economics of technological change has been sidetracked to secondary questions, such as whether a particular technology was relatively labor- or capital saving, or what the effect of cyclical variation in demand was on the rate of patenting.

One distinction between different types of technological progress was made by Francis Bacon. In his view, inventions came in two categories, those that depended on the overall state of knowledge and thus could be made only when the scientific and informational background became available, and those that were purely empirical and that could therefore have been made at any time in recorded history. In practice, this distinction is not always easy to make. Some apparently empirical inventions did in fact depend on subtle changes in the understanding and assumptions of the inventor about his or her physical environment, or changes in the availability of a crucial material or component that made the invention practical. Thus, as Cardwell (1968) points out, Bacon was mistaken when he asserted that moveable-type printing could well have been invented by the ancient Greeks, because it depended on medieval advances in metallurgical technology. Yet it is clear that in many cases there is indeed no good reason why an invention was made at a particular point in time and not centuries earlier. It is tempting to argue that lack of perceived need or demand was responsible, but it is also possible that a particular innovation simply did not occur to anyone before. Some medieval inventions of great usefulness and simplicity, such as the wheelbarrow and the stirrup, must be classified in this category.

There is a rich tradition among economists interested in technological change distinguishing between invention and innovation. Schumpeter pointed out that invention does not imply innovation, and that it was innovation that provided capitalism with its dynamic elements. Invention, by that logic, is in itself of limited interest to

economists. Ruttan (1971, p. 83) has proposed more or less to abandon the concept of invention altogether and regard it merely as an "institutionally defined subset of technical innovation." Again, these distinctions are not always helpful. During the implementation stages, inventions were usually improved, debugged, and modified in ways that qualify the smaller changes themselves as inventions. The diffusion of innovations to other economies, too, often required adaptation to local conditions, and has in most cases implied further productivity gains as a result of learning by doing.

Before we rashly decide that inventions should not be the focus of the study of the economic history of technological change, it may be useful to reflect further upon the issue. An invention should be defined as an increment in the set of the total technological knowledge of a given society, which is the union of all sets of individual technological knowledge.⁴ It is possible to argue that this set is itself not a meaningful concept, but without it, most cultural and intellectual history makes little sense. More important, it could be objected that this set is irrelevant. New knowledge that is not applied makes no difference to economic welfare, whereas the bulk of Schumpeterian economic growth comes from the application of *old* knowledge. To state it in somewhat different terms, at any moment there is a large gap between *average*- and *best-practice* technology; reducing this gap by disseminating the techniques used by producers at the cutting edge of knowledge is technological progress without invention. The diffusion of technology from advanced regions or countries to backward ones also represents technological progress without invention. But inferring from these observations that invention should therefore not be at the center of any discussion of the history of technology in economic growth would be unwarranted. Any discussion of the gap between average- and best-practice techniques makes little sense unless we have some notion of where the best-practice technique came from in the first place. Without further increments in knowledge, technological diffusion and the closing of the gap between practices will run into diminishing returns and eventually exhaust itself. It is thus incumbent on us to examine the cases in which this exhaustion has not occurred and to ask why.

To put it differently, a basic premise of this book is that invention and innovation are complements. In the short run, this complementarity is not perfect; it is indeed possible to have one without the other. But in the long run, technologically creative societies must be both inventive and innovative. Without invention, innovation will

4. Strictly speaking, the society over which this set is defined should be all of humanity. In the case of largely disjoint parts of humanity it seems to make sense to restrict this set somewhat so that it is possible to speak of independent inventions.

eventually slow down and grind to a halt, and the stationary state will obtain. Without innovation, inventors will lack focus and have little economic incentive to pursue new ideas. I shall argue in Part III that this complementarity is one of the reasons so few societies have been technologically creative. Many diverse conditions have to be satisfied simultaneously. Invention depends on factors that determine individual behavior, as the inventor is ultimately alone in his or her attempt to make something work. Innovation, on the other hand, requires interaction with other individuals, depends on institutions and markets, and is thus largely social and economic in nature.

No single answer to the question of why technological creativity occurs in some societies and not in others will ever satisfy everyone. "A single comprehensive general law of evolution," wrote Gerschenkron (1967, p. 448), "lies on the other side of the line that separates serious research from fanciful superficialities." Yet clearly we can say more than simply that "everything mattered" or identify the salient differences between creative and uncreative societies, respectively, and draw a causal relationship accordingly. Correlation does not prove causation. Ireland's Catholicism, central Africa's climate, and Southeast Asia's dependence on rice have all been falsely identified as causal factors in the lack of technological creativity in these societies. Economic analysis can help us to identify some factors as important, to cast doubt on others, and to design tests to assess those factors that are ambiguous from a theoretical point of view.

To see how and why technological creativity occurs, we thus must distinguish two basic components in the invention-innovation sequence. The first component is that technical problems involve a struggle between mind and matter, that is, they involve control of the physical environment. Nature, it is said, yields her secrets in a niggardly manner. Teasing these secrets out of her and then manipulating them for material benefit is the essence of any technological breakthrough. The outcome is determined by the daring and ingenuity of the inventor, the limitations of the materials and tools at his or her disposal, and the resistance of the laws of nature to bending to the inventor's will. The other component is social. For a new technique to be implemented, the innovator has to interact with a human environment comprised of competitors, customers, suppliers, the authorities, neighbors, possibly the priest. For a society to be technologically creative, three conditions have to be satisfied. First, there has to be a cadre of ingenious and resourceful innovators who are both willing and able to challenge their physical environment for their own improvement. Innovation of any kind is unlikely in a so-

ciety that is malnourished, superstitious, or extremely traditional. Second, economic and social institutions have to encourage potential innovators by presenting them with the right incentive structure. In part, such incentives are economic; technological creativity is more likely if an innovator can expect to become rich. Noneconomic incentives can matter too, however. A society can reward successful innovators by awarding them medals, Nobel prizes, or intangible symbols of prestige. Third, innovation requires diversity and tolerance. In every society, there are stabilizing forces that protect the status quo. Some of these forces protect entrenched vested interests that might incur losses if innovations were introduced, others are simply don't-rock-the-boat kinds of forces. Technological creativity needs to overcome these forces.

An essay on the economic history of technological change inevitably contains dates, names, and places. By its nature, the tale of technological creativity requires citing who first came up with an idea and who made the critical revisions and improvements necessary for the idea to work. Yet in the past decades, economic historians have not practiced this type of history. As David (1987) asks, does technology not simply accumulate continuously from the incremental, almost imperceptible, changes brought about by a large number of anonymous people? Some historians insist that almost all invention consists of this "technological drift" (as Jones, 1981, p. 68, has termed it), consisting mostly of anonymous, small, incremental improvements (Rosenberg, 1982, pp. 62–70). As a reaction to heroic theories of invention in which all improvements are attributed to individual geniuses, the drift theory has been justly influential. But is it not possible to go too far in the other direction and give too little credit to major inventions made by a vital few? Some inventions, such as the printing press, the windmill, and the gravity-driven clock, contradict the generality of the gradualist model of technological progress. There have been, and probably always will be, large and discrete changes in technology that sweep the world off its feet and make it rush in to acquire and imitate the novelty. Modern research has shown, to be sure, that most cost savings are achieved through small, invisible, cumulative improvements. But improvements in what? Virtually every major invention was followed by a learning process, during which the production costs using the new technique declined; but for these costs to fall, the novelty had to be invented in the first place. An adult weighing 150 lbs has acquired about 95 percent of his or her weight since birth—does that mean that conception is not important?

In discussing the distinction between minor inventions, whose cumulative impact is decisive in productivity growth, and major tech-

nological breakthroughs, it may be useful to draw an analogy between the history of technology and the modern theory of evolution, a comparison that I shall pursue in Chapter 11. Some biologists distinguish between micromutations, which are small changes in an existing species and which gradually alter its features, and macromutations, which create new species. The distinction between the two could provide a useful analogy for our purposes. I define *microinventions* as the small, incremental steps that improve, adapt, and streamline existing techniques already in use, reducing costs, improving form and function, increasing durability, and reducing energy and raw material requirements. *Macroinventions*, on the other hand, are those inventions in which a radical new idea, without clear precedent, emerges more or less ab nihilo. In terms of sheer numbers, Microinventions are far more frequent and account for most gains in productivity. Macroinventions, however, are equally crucial in technological history.

The essential feature of technological progress is that the macroinventions and microinventions are not substitutes but complements. Without subsequent microinventions, most macroinventions would end up as *curiosa* in *musea* or sketchbooks. Indeed, in some historical instances the person who came up with the improvement that clinched the case receives more credit than the inventor responsible for the original breakthrough, as is the case of the steam engine, the pneumatic tire, and the bicycle. But without novel and radical departures, the continuous process of improving and refining existing techniques would run into diminishing returns and eventually peter out. Microinventions are more or less understandable with the help of standard economic concepts. They result from search and inventive effort, and respond to prices and incentives. Learning by doing and learning by using increase economic efficiency and are correlated with economic variables such as output and employment. Macroinventions, on the other hand, do not seem to obey obvious laws, do not necessarily respond to incentives, and defy most attempts to relate them to exogenous economic variables. Many of them resulted from strokes of genius, luck, or serendipity. Technological history, therefore, retains an unexplained component that defies explanation in purely economic terms. In other words, luck and inspiration mattered, and thus individuals made a difference. Scholars who cast doubt on the importance of individuals often rely on a dispensability axiom: if an invention had not been made by *X* it would have been made by *Y*, a conclusion typically inferred from the large number of simultaneous discoveries. Although this regularity holds true for some inventions, including the telephone and the incandescent lightbulb, it is not applicable to scores of other important inventions.

If there is any area in which a deterministic view that outcomes are shaped inexorably by forces stronger than individuals—be they supply and demand or the class struggle—is oversimplified, it is in the economic history of technology. Asking whether the major breakthroughs are more important than the marginal improvements is like asking whether generals or privates win a battle. Just as in military history we employ shorthand such as “Napoleon defeated the Prussians at Jena in 1806,” we may say that a particular invention occurred at this or that time. Such a statement does not imply that individual inventors are credited with all the productivity gains from their invention any more than the statement that Napoleon defeated the Prussians implies that he single-handedly defeated an entire army. It is useful to organize the narrative around the discrete event.

The distinction between micro- and macroinventions is useful because, as historians of technology emphasize, the word *first* is hazardous in this literature. Many technological breakthroughs had a history that began before the event generally regarded as “the invention,” and almost all macroinventions required subsequent improvements to make them operational. Yet in a large number of cases, one or two identifiable events *were* crucial. Without such breakthroughs, technological progress would eventually fizzle out. Usher (1954, p. 64) emphasized the importance of “the art of insight,” and although he insisted that no single individual was uniquely necessary, he also recognized that individual qualities and differences were at the center of the process.

This study will necessarily draw from a small sample and be heavily biased toward Western economic history. Before I can turn in Part III to an analysis of why some societies were creative and others were not, it is imperative to survey the facts. Too much writing about the economic aspects of technological progress takes place in an historical vacuum, or creates factual artifacts in which events and facts convenient to the author’s interpretation are plucked selectively from the record. A more comprehensive knowledge of the main currents of technological history restrains the urge to make generalizations. In Part II, therefore, I summarize the main technological developments of the past 25 centuries. Such an undertaking seems absurdly ambitious: the five-volume *History of Technology* edited by Charles Singer and others and published in the late 1950s contained 4,000 pages of text and yet is widely considered incomplete. My intention is to survey only the most important innovations in a limited number of areas. I leave out the prehistoric and very early eras, as well as the post-1914 period. Even so, between about 500 B.C. and 1914 there is a record so stupefyingly abundant in facts and evidence, that I can only scratch the surface of a deep and rich seam. By largely

ignoring civil engineering, architectural, medical, and military technology, and focusing only on those developments that demonstrably affected living standards, I have kept the survey within manageable proportions.

Following the historical survey, I analyze the differences between creative and uncreative economies. In Chapter 7 I lay out a series of explanations ranging from nutrition to religion, from institutions to values and *mentalités*. To examine the importance of those factors, in Chapters 8, 9, and 10 I apply them to three comparative studies—classical society versus the medieval West, China versus Europe in the post-1400 period, and the Industrial Revolution in Britain and the rest of Europe and the eventual decline of Britain as a leading technological society—that juxtapose societies that were technologically dynamic with others that were not.

Part IV looks at the dynamics of technological change. Specifically, it asks whether technological change occurs in leaps and bounds, or whether it takes place gradually and continuously. To answer this question, I set up an analogy between technological progress and biological evolution, and try to apply the concept of punctuated equilibrium to the analysis of technology.

The history of technological progress is open to accusations of "Whiggishness." It tends to be a tale of progress, of improvement, of the irrepressible advance toward a better and richer age. Given the difference between the standard of living in the West today and three centuries ago, I find criticisms of Whiggishness easy to ward off. E. H. Carr (1961) tells the tale of Czar Nicholas I, who was reputed to have issued an order banning the word *progress* from his realm, and adds acerbically that historians of the West have belatedly come to agree with him. It seems hardly open to dispute that what has happened to people's ability to manipulate the laws of nature in the service of economic ends is unidirectional and deserves the word progress. Without assessing the wider repercussions of changing technology on noneconomic intangibles, such as liberty and brotherly love, an economist's judgment of history, colored by the evidence of the perpetual struggle against poverty and drudgery, finds technological change worthy of the word progress. Of course, if technological change eventually leads to the physical destruction of our planet, survivors may no longer wish to use the word progress in their descriptions of technological history. Until then, however, I feel justified in using the term, not in the teleological sense of leading to a clearly defined goal, but in the more limited sense of direction. If the same bundle of goods can be produced at lower cost, provided that these costs are accurately measured to include social costs such as environmental damage—the term progress is suitable.

Yet the central message of this book is not unequivocally optimis-

tic. History provides us with relatively few examples of societies that were technologically progressive. Our own world is exceptional, though not unique, in this regard. By and large, the forces opposing technological progress have been stronger than those striving for changes. The study of technological progress is therefore a study of exceptionalism, of cases in which as a result of rare circumstances, the normal tendency of societies to slide toward stasis and equilibrium was broken. The unprecedented prosperity enjoyed today by a substantial proportion of humanity stems from accidental factors to a degree greater than is commonly supposed. Moreover, technological progress is like a fragile and vulnerable plant, whose flourishing is not only dependent on the appropriate surroundings and climate, but whose life is almost always short. It is highly sensitive to the social and economic environment and can easily be arrested by relatively small external changes. If there is a lesson to be learned from the history of technology it is that Schumpeterian growth, like the other forms of economic growth, cannot and should not be taken for granted.

PART TWO

NARRATIVE

CHAPTER TWO

Classical Antiquity

Until recently, the consensus on classical civilizations (Greek, Hellenistic, and Roman) was that these societies were not very successful technologically (Finley, 1965, 1973; Hodges, 1970; Lee, 1973). As some recent critics have pointed out, such a judgment is overly harsh (K. D. White, 1984). First, some significant technological breakthroughs were made during classical times, and their extent is likely to be underrated by historians because of the scant literary and archaeological evidence remaining. Second, the notion that science could be applied to concrete objectives rather than be admired for its own sake was certainly present, and was particularly well developed among the Hellenistic mechanicians. Third, as Finley (1973, p. 147) emphasizes, in some sense the harsh judgment of classical societies imposes our own value system on a society that had no interest in growth. "As long as an acceptable life-style could be maintained, however that was defined, other values held stage." In the areas that mattered most to *them*, the Greeks and Romans achieved huge successes. Cipolla (1980, p. 168) adds that because our own society has a civilization that is mechanistic, we tend to identify technology to a large extent with mechanics, whereas classical civilization was oriented toward other forms of technology. Some of the important achievements of classical technology were in those aspects of technology that were nonphysical in nature: coinage, alphabetization, stenography, and geometry were part of the information-processing sphere rather than the physical production sphere of the economy. Even when their achievements were in the physical sphere, they were mostly in construction and architecture, rather than in mechanical devices. Nonetheless, the judgment reflects our instinctive disappointment with a civilization that celebrated such triumphs in literature, science, mathematics, medicine, and political organization.¹ Even in nonmechani-

1. In contrast, the early Iron Age (1100 B.C. to 500 B.C.) saw, in addition to the development of the use of iron, the development of most carpenters' tools (lathes, saws, pegs), shears, scythes, axes, picks, and shovels; the invention of the rotary quern (used to grind flour and ores); and improvements in the construction of ships and wagons.

cal aspects of technology, such as chemistry and farming, the record of the classical world seems to fall short of what appears to us to have been its potential.

What technological progress there was in the classical world, especially in Roman times, served the public, rather than the private, sector. Roman leaders acquired popularity and political power by carrying out successful public works. The history of the Roman Empire, especially, reveals the importance of men such as Agrippa and Apollodorus, who helped their respective masters (Augustus and Trajan) carry out vast public works. The Rome of 100 A.D. had better paved streets, sewage disposal, water supply, and fire protection than the capitals of civilized Europe in 1800. Most agriculture, manufacturing, and services were carried out by the private sector, however, and achievements there were few and slow. The major areas for which the Greeks and Romans became famous were in civil and hydraulic engineering and architecture. Water conduits, built for both the supply of fresh water and for drainage, date from early classical Greece.² The Roman Empire, which commanded enormous resources, brought public-good engineering to great heights, although most of its engineering feats, including roads and aqueducts, utilized existing technology. The supply of Rome with water was begun by Appius Claudius in 312 B.C., and the system reached unprecedented complexity by the first and second centuries A.D.³ Sewage and garbage disposal were also highly developed. A system of central heating was developed for use in both homes and bathhouses. In describing the urban bias in Roman technology, Hodges (1970, p. 197) concludes that "the Roman city was more interesting for its scale than for the novelty of its design."

Equally important in Roman engineering was the infrastructure of land transport: the roads and bridges built by the Romans are justly admired as one of their greatest achievements. Much of the success here was due to their discovery of cement masonry, which Forbes (1958b, p. 73) has called "the only great discovery that can be as-

2. The first such large project, the Samos aqueduct, was built by Eupalinus of Megara, around 600 B.C. It brought water from a lake to the town along a tunnel about a mile in length and 8 ft. in diameter.

3. By the time of the water superintendent Frontinus, writing between 97 and 104 A.D., many houses in Rome had hot and cold running water. The use of lead pipes was an ingenious solution to the short supply of construction material, but may have had severe side effects on the population's health. Interestingly enough, Roman writers were aware of the problems of lead poisoning, but their warnings were not heeded, and it was not until the time of Benjamin Franklin that lead poisoning was again identified as a hazard (K. D. White, 1984, pp. 164-65).

cribed to the Romans."⁴ The economic significance of Roman roads should not be exaggerated. The roads that survived deep into the Middle Ages were those that were not used, whereas most of the heavily traveled and poorly maintained roads of Gaul became unusable. Roman roads were built for military purposes and their use by the general public for the purpose of trade was incidental (Leighton, 1972, pp. 48–60). Late imperial governments imposed severe limitations on the weight that could be hauled, and without the complementary technology of horse harnessing and shodding and wagon building their economic impact was probably limited to high-value, low-weight cargoes. Roman roads were steeply graded, which did not matter much for the movement of infantry and light loads, but proved too cumbersome for commercial loads.⁵ In bridges and aqueducts, the Romans used the revolutionary technique of weight-supporting arches or pillars made of cement. Some of their aqueducts, such as the famous Pont du Gard near Nîmes, have survived. Others, such as the wooden trestle bridge that Julius Caesar's troops built on the Rhine in 10 days (in 55 B.C.), are known to us only from documents.

Another area in which technical ingenuity improved efficiency in the public sector was in the construction of war machines. Although military technology is not of major concern here, it is worth noting that Greek and Roman military technology provides one of the few areas of a successful collaboration between scientists and technology.⁶ Strangely, the Romans did not improve much on Greek and Hellenistic military machines, although they used them extensively and built bigger and more powerful versions.

In what we would today call *machines*, the contribution of the classical world, especially Hellenistic civilization, was in recognizing fully the importance of the elements of machines, such as the lever, the wedge and the screw, as well as the elements of motion transmission, such as the ratchet, the pulley, the gear, and the cam. Yet these insights were applied mostly to war machines and clever gadgets that

4. This credit is not entirely deserved, since cement was used in Asia Minor before it was used in Rome. But the Romans vastly improved its use, and employed such quality control that they may well be thought of as the originators of the technique. Specific to Roman construction was the use of waterproof cement, known today as *pozzolana*, made from the volcanic dust found near Naples.

5. The cost of transporting goods over land remained more than 20 times higher than the cost of carrying them by sea (Greene, 1986, p. 40).

6. The story of Archimedes helping to build war machines in a futile attempt to defend his native Syracuse against Roman armies is well known (Hacker, 1968). Other engineers who made major contributions to the construction of catapults are Ctesibius (third century B.C.) and Philo of Byzantium (about 180 B.C.).



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